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MONTANA ENERGY CONSERVATION PLAN

Working Paper No. 7

SOLAR ENERGY

JUL 1977
STATE DOCUMENTS

A Report to the

Montana Energy Advisory Council

Prepared for

The Montana Energy and MHD Research and Development Institute, Inc.
Butte, Montana

By

The Ecotope Group
Seattle, Washington

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General Statement of Findings

1. There is a well developed technology for collecting solar heat in the temperature range from room temperature to 1000°F. (See Table 7.1)

2. The costs of heat collected range from $5.00/mBTU to $10.00/mBTU, regardless of temperature.

3. Systems which involve concentration and/or tracking perform relatively better in Montana than the tradiational flat plate collection systems.

7.0 SOLAR

7.1 Introduction and Background

Current astronomical thinking conjectures that the sun is a young star, large enough and dense enough to create such pressures and temperatures at its core (20,000,000°C) that 400 tons per second of itself is converted to pure energy. This energy ultimately leaves the surface (5,000°C) of the sun in the form of electromagnetic waves and very energetic particles. The outer layers can be seen with instruments as a seething incandescent sea, home to many complicated processes not yet understood. It is only within the past 75 years that we have come to understand even the basic processes of the sun and its similarities to the stars.

The energy leaving the sun reaches the earth 93,000,000 miles away within eight minutes. Most of this energy is in the form of light which is visible or near visible. Outside the atmosphere this light has an intensity of approximately 1353 watts per square meter (almost two horsepower/square yard) referred to as the "solar constant". The intensity of the light is diminished to about one horsepower/ sq.yard upon the earth's surface after passing through the atmosphere. The atmosphere has absorbed, reradiated or scattered about 40% of the light. Thus, the light received on the earth's surface is in two forms: the direct beam image of the sun and the diffused light from scatter and reradiation by the atmosphere.

In a very clear area, up to 80% of the energy received is in the form of direct light. Most areas receive about 60% of the solar energy as direct light. This distinction between direct and diffused light is important because many solar collecting devices involve mirrors or lenses to focus light, and in most cases only the direct light is focusable.

The technology for using the energy of light was well developed about 70 years ago. The largest solar power plant built to date was built in 1913 in Cairo, using engineering very similar to that being researched now. The technology has not been used because it has not been economically competitive with the relatively cheaper, but non-renewable, fossil fuels. Considerable public interest and engineering ingenuity were directed towards solar power near the turn of the century. The solar power plant in Cairo was backed financially by many important American and British investors, and the project caught the interest of intelligent, far-seeing scientists throughout Europe. Unfortunately, with the advent of WWI, the project was dismantled (Clark, 1974).

In this study, the state of the solar art is examined for promising devices which will convert sunlight either into heat or electricity. Detailed descriptions of specific candidate devices are given in Section 7.6. A general description of each type of device is following as background.

7.2 Solar Collection Devices

7.2.1 Flat Plate Collectors

These are essentially flat surfaces which retain the heat of the sunlight incident upon them. This heat is transferred to some useful purpose by circulating air or a fluid such as water along the warm surface to pick up heat and move it to the point of use. Useful quantities of heat at temperatures up to 200°F can be collected this way. The key to retaining the heat of the incident light is the glazing over the surface which serves to admit the light readily, but which retards the loss of heat. The loss of heat from the surface can be further reduced by adding more glazing and/or by special treatment of the surface, called a selective surface.

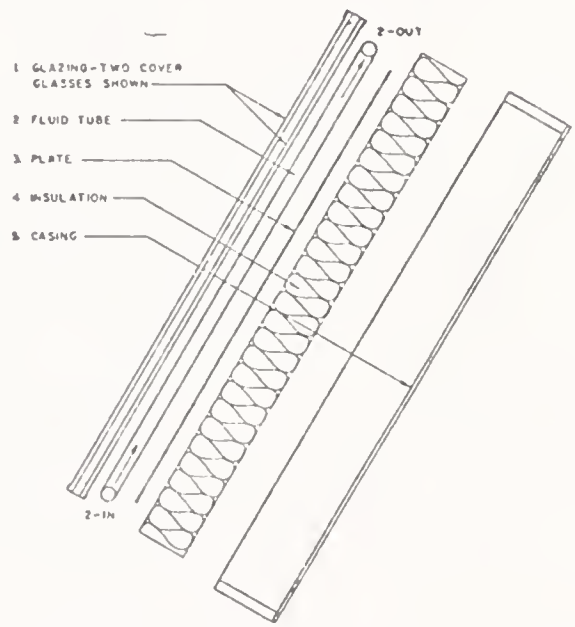


Figure 7.1
Typical cross section for a flat plate collector

Source: Yellot, 1974

The limitations of flat plate collectors are well-documented. The large absorption area which equals the aperture presents a large area for heat losses. For example, a flat plate collector with two glazings of glass and a selective coating, operating at 200°F, will lose about 100 BTU per sq.ft. of the 250 BTU's which are incident upon the surface of the absorber. A concentrating collector operating at 200°F, with an absorber one-fifth the size of the flat plate but of equal aperture, will lose only one-fifth as much heat. Although flat plates can utilize the diffuse component of the light, its contribution is minimal, and these collectors are still dependent on the direct radiation for the majority of the energy converted.

7.2.2 Two-Dimensional/Linear Focusing/Trough Concentrators

These involve mirrors or lenses to concentrate the sunlight onto a relatively small area. High temperatures result as the area heats up in an attempt to rid itself of the energy directed upon it. The target of the linear-focused light is generally a tube which is coated with a thin selective film to absorb and retain the radiation. The tube is usually insulated by either a clear evacuated tube which encompasses it or by an insulated linear cavity

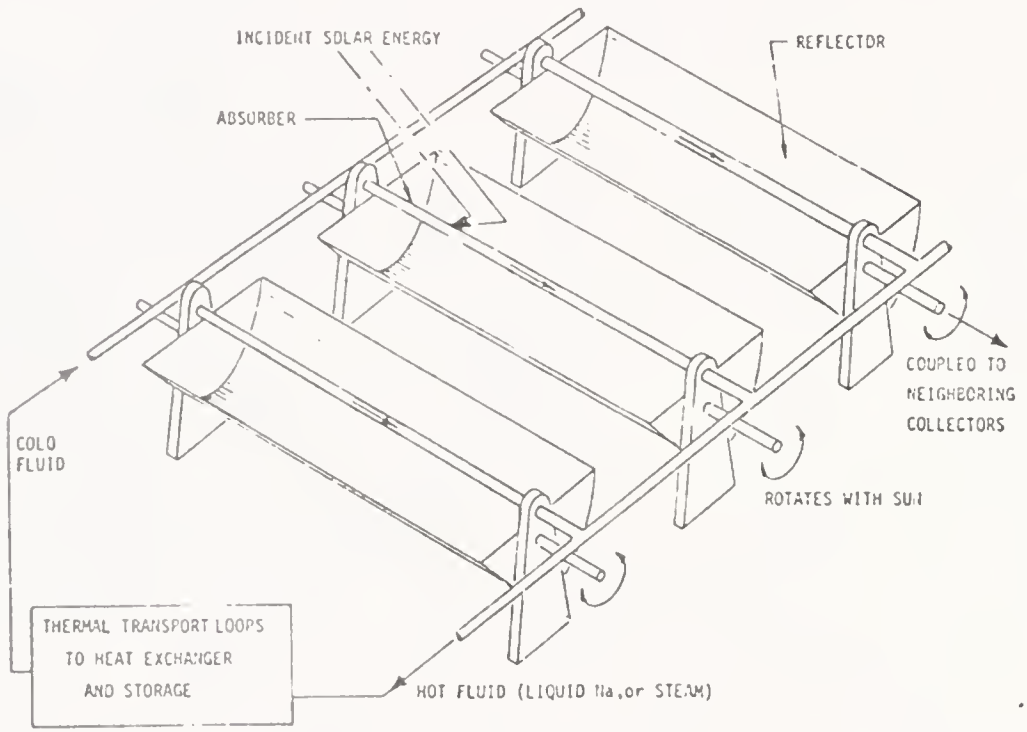


Figure 7.2
Element of Parabolic Trough Solar Collector Array

Source: Boeing, 1973

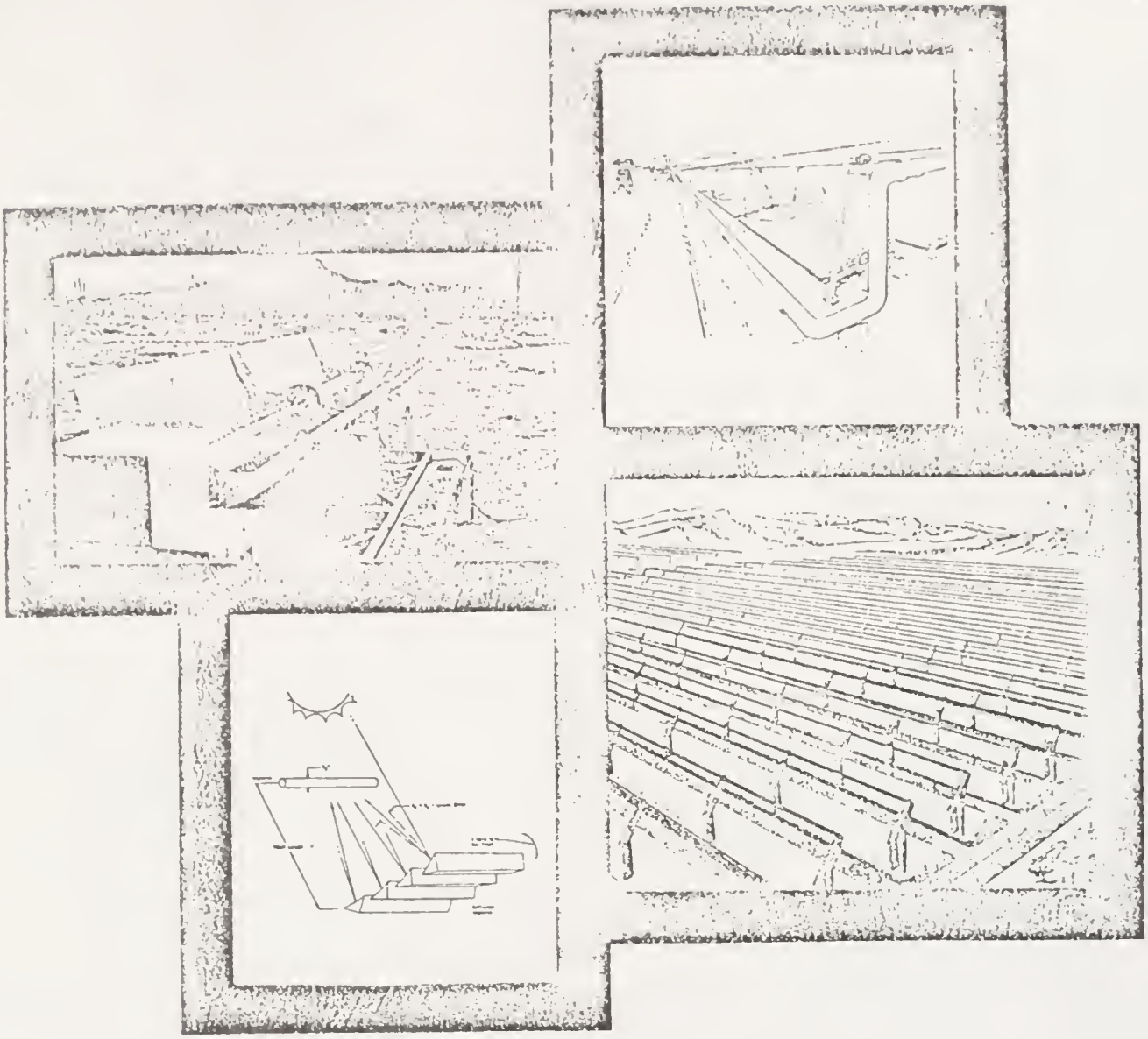


Figure 7.3
Linear Focusing Type Collectors

Source: Aerospace, 1975

This collector is characterized by its ability to track the sun's diurnal path in a two-dimensional plane. This is done by either moving the reflector or lens or by moving the target (collector tube).

These systems are generally superior to flat plate collectors; they operate at much higher temperatures (outlet temperatures to 1000°F with efficiencies of 50% for the entire day). (Russell, 1976, Personal)

Linear focusing collectors can achieve concentration ratios up to 100 X, limited by the fact that the sun is not a point, but subtends a half of a degree arc in the sky. A unique quality of the collector tube which absorbs the concentrated energy is that it does not have a uniform temperature along its entire axis. Between the inlet and the outlet of any sufficiently long absorber tube with a flowing coolant, there is an established gradient, the average of which represents the heat loss of the linear tube absorber. This is a remarkably efficient way to transfer heat and minimize losses during that transfer. For example, an absorber tube with an average temperature of 600°F could deliver an outlet heat of 1000°F if the inlet temperature is at 200°F. (Goralnick, 1975)

7.2.3 Dish

Dish concentrators are characterized by their point concentration from a dish-shaped cone, hemisphere, paraboloid of revolution, etc. These concentrators are similar (almost identical) in efficiency and operation to a heliostat with respect to tracking the sun from sunrise to sunset.

Dishes differ from heliostats in that they suffer some problems with regards to piping and transport of energy or coolant to its source of use. A variation of the dish, in which the target moves rather than the dish, might offer some interesting savings in tracking mechanics, but will not be as efficient as moving the whole mirror to track the sun. Enaes used a conical dish-type collector to power his 1904 irrigation pump near Tempe, Arizona. (Clark, 1974)

Figure 7.4
Paraboloid with Cavity Absorber

Source: CSA, 1973

7.2.4 Heliostats

Heliostats describe a group of concentrating systems which utilize a field of fully gimbaled mirrors or reflective surfaces to direct the beam radiation onto a central receiver. The receivers are usually characterized as towers with absorber. Most of these absorbers are inside cavities that have relatively small openings through which light is directed from the entire field of reflectors. The light, once passed into the cavity, is trapped and converted into thermal energy which is carried away to be converted to mechanical and ultimately electrical energy

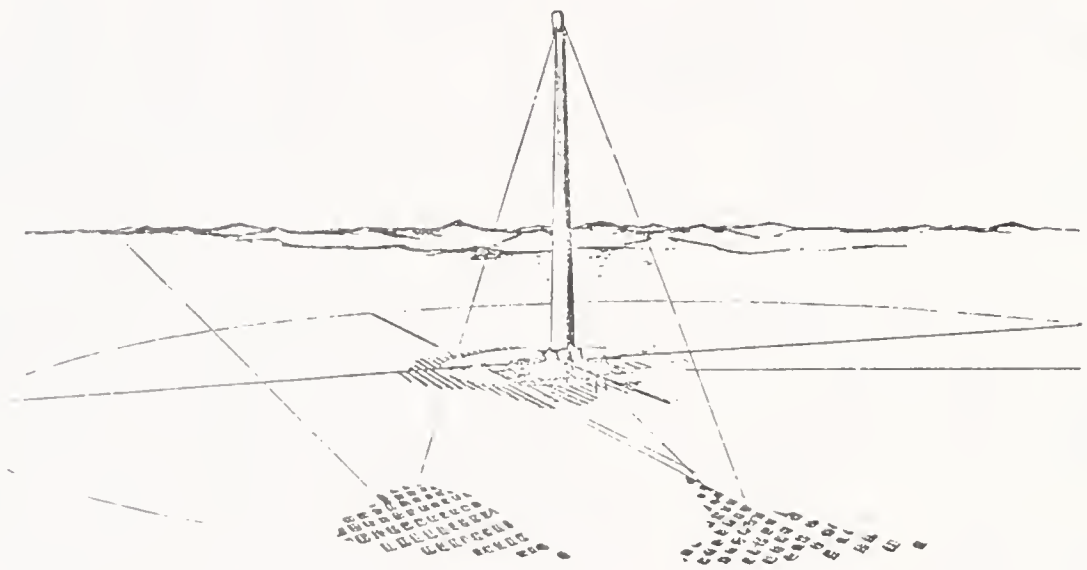


Figure 7.5
Artist's conception of a tower heliostat solar generating facility

Source: Connell, 1974

The larger the installed capacity of the solar installation, the larger the field of mirrors and, thus, the height of the receiver tower. For example, a 215 MW_e plant in Arizona would have a tower about 1500 feet in height. (Powell, 1975) Other schemes call for reflector fields on southerly inclines directing light to several low towers rather than from a level surface up to a single high tower.

A well-known working example of the heliostat central receiver concept is the 1000 kw solar furnace at the French CNRS solar energy laboratory in Odeillo-Font Romeu. The furnace utilizes a field of mirrors on a southerly facing incline directed at a parabolic reflector. The parabolic reflector is the north wall of a nine-story building and the reflector directs the beam into a furnace cavity housed by a south-facing tower. With concentrations of 6000:1, this furnace can exceed temperatures of 3800°C.

Tower heliostat systems can be very efficient compared to other systems for solar thermal/electric applications. They solve the high cost problems of piping, and they provide high plant factors because they track the sun through its diurnal path across the sky.

One limiting factor is their inability to operate in high wind conditions. The wind loading factor for most mirrors is about 30 mph (Brumleve, 1976, Personal). There is a great deal of uncertainty associated with boiler design and their ability to withstand sudden or uneven heating.

7.2.5 Photovoltaics

Photovoltaics convert sunlight into electricity directly by using the momentum of the sunlight, knocking electrons free to become an electric current. Photovoltaics are used in flat plate configurations and in concentrators to enhance the aperture without incurring the additional cost of more cells. The current drawback to use of photovoltaics is the cost. Dramatic cost decreases are projected as the cells become widely used and technology improved.

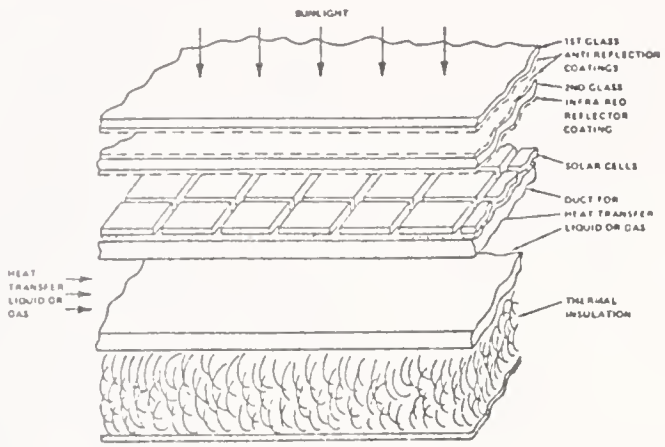


Figure 7.6
Photovoltaic solar array construction for terrestrial applications

Source: Wolff, 1975

7.3 Summary of Analytic Results

7.3.1 Representative systems which appear promising for application in Montana have been selected from the broad set of solar collection devices. A summary of the expected performance and costs of these options is given in Table 7.1.

7.3.2 The methods by which these collection systems are assessed for Montana conditions are given in detail in Section 7.5.

7.3.3 The primary solar data, and the modifications made to it, are described in Section 7.4.

Table 7.1

Solar Energy Collection Options

System temperature	system type	Cost/$ sq.ft.	Area to collect mBTU/yr sq ft.	Capital cost $/mBTU/yr	Energy cost $/mBTU	Status	Context
Room temperature 70°F	Double glazed window[1] with R=10 night door	8.00	4.9	39.60	4.46	Standard construction practice	passive space heating in day and portion of night depending on storage
Hot water temperature 130°F	Flat plate collector double glazed selective surface[2]	6.00 23.00	5.8	34.80 133.00	3.98 13.80	home built materials only/ or off-the-shelf system	hot water or space heati This is one of the best flat plate collectors tested by NASA and yield is still low in Montana' cold climate.
	fresnel refractive concentrator (tracking)[2]	21.50	2.3	50.70	5.57	off-the-shelf system	hot water or space heati
220°F	fresnel refractive concentrator (tracking)[2]	21.50	4.6	99.08	10.40	off-the-shelf	very hot water or low-grade steam or refrigeration
	evacuated tube collector (stationary)[3]	28.00	3.34	93.65	9.86		

1. Calculation performed on window at 45° and therefore may overestimate solar gain while the costs/sq. ft. of construction were also overestimated.
2. Calculations on solar data from Great Falls.
3. Calculations on solar data from Glasgow.

Table 7.1
Solar Energy Collection Options, Cont.

system temperature	system type	Cost/$ Sq.ft.	Area to collect mBTU/yr sq.ft.	Capital cost $/mBTU/yr.	Energy cost $/mBTU	Status	Context
300°F	3x concentrator with evacuated receiver[3]	10.00 stat. 13.00 track.	5.26 3.31	52.60 43.05	5.76 4.81	prototype under construction at Argonne Labs	costs are estimates only
600°F	Linear concentrator; fixed mirror tracking absorber[3]	8.04	4.26	34.21	3.92	prototype built and tested, General Atomic Corp.	high temperature process heat costs are based on large scale installation and components made in specifically assigned manufacturing facilities
	linear concentrator; stationary absorber at focus of articulated fresnel slats [3]	9.32	4.26	39.65	4.47	prototype built and tested, Itek Corp., Sheldahl Corp.	
	linear concentrator; articulated parabolic trough[3]	9.36	3.85 E-W axis 2.81 turntable	36.04 26.29	4.10 3.12	prototype built and tested, Honeywell Corp., Sandia Labs	
1000°F	heliostat tower [3]	26.26 thermal only 28.76 thermal electric	2.27	59.54 200.64 if electric output only, & other heat rejected	6.42 20.56 (70mils/kwh)	essential components built; prototype sys. to be completed 1977	high temperature process heat or thermal electricity. Costs based on 337 mw thermal installation.

7.4 Assessment of Montana Solar Conditions

7.4.1 The sun position (azimuth and elevation) for various times of day and seasons is given in Figure 7.7. This chart is based on 48° North latitude and should be reasonably accurate throughout the state.

7.4.2 Daily solar radiation measurements have been made at Glasgow and Great Falls by the National Weather Service using an Epply (T.M.) Pyranometer. These are only measurements of solar radiation incident upon a horizontal surface. Various transformations are used to give estimates of solar radiation on a variety of un-horizontal surfaces. A discussion of these transformations and definitions of the various surfaces are found in Section 7.5. Solar radiation for Great Falls and Glasgow and other related weather data are given in Tables 7.2 and 7.3 with estimates of direct or focusable radiation for several types of tracking surfaces. This forms the basis for predicting the performance of various types of focusing solar collectors.

7.4.3 Percent possible sunshine, based on National Weather Service measurements at various Montana cities, is shown in Table 7.4. These cannot be regarded as accurate solar radiation measurements, but they are included here in an attempt to generalize the Great Falls and Glasgow solar measurements to other Montana cities where actual solar measurements were not taken. From this it will be assumed that Great Falls solar measurements also apply to Billings, Havre and Helena, and

48° NORTH LATITUDE SUN CHART

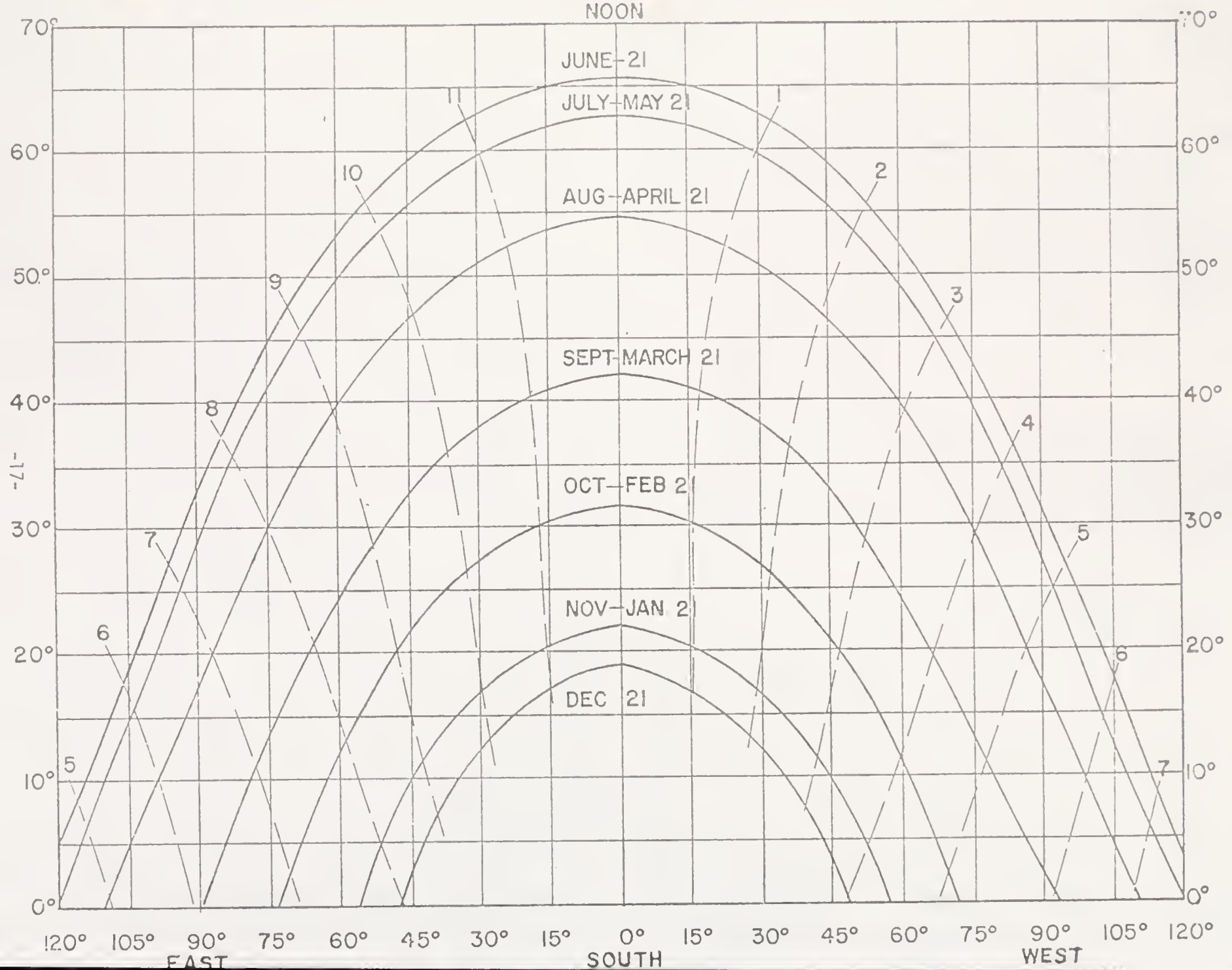


Table 7.2

Glascow, Montana: General Solar Analysis Data

Btu/ft^2 day

Month	total solar radiation including diffuse		focusable (Direct) solar radiation (excluding diffuse)						Day Length hrs.	.Days/ Month	Day Avg.t °F	Nigh Avg. °F
	Hor. Total	45° Total	Hor.	45°	full sun tracking	Turn-table	N-S polar	N-S Horizontal				
Jan	568	1455	418	1318	1441	1268	1340	763	7	31	14	4
Feb	951	1896	739	1692	2159	1943	2094	1439	9	28	20	10
Mar	1419	2069	1092	1758	2594	2389	2568	2082	11	31	31	20
April	1718	1842	1209	1392	2081	2026	2060	1867	11	30	49	36
May	2094	1906	1487	1365	2462	2356	2339	2339	13	31	61	48
June	2231	1886	1574	1304	2404	2310	2212	2317	13	30	68	56
July	2378	2106	1800	1564	2839	2719	2641	2726	13	31	77	64
Aug	1958	1986	1440	1512	2557	2431	2480	2356	13	31	76	62
Sept	1512	1959	1128	1604	2268	2152	2268	1928	11	30	64	51
Oct	984	1703	716	1460	1790	1654	1754	1264	9	31	53	40
Nov	568	1291	389	1136	1210	1080	1149	669	7	30	34	24
Dec	428	1145	290	1025	1057	919	783	546	7	31	22	12

Source: National Weather Service via Baker, 1976

Table 7.3

Great Falls, Montana: General Solar Analysis Data

Btu/ft^2 day

Month	total solar radiation including diffuse		focusable (Direct) solar radiation (excluding diffuse)						Day Length hrs.	Days/ Month	Day Avg.t °F	Night Avg.t °F
	Hor. Total	45° Total	Hor.	45°	full sun tracking	Turn-table	N-S polar	N-S Horizontal				
Jan	516	1204	345	1057	1189	1046	1105	629	7	31	25	16
Feb	855	1580	606	1359	1770	1593	1717	1180	9	28	31	22
Mar	1349	1901	994	1576	2361	2174	2337	1895	11	31	35	26
April	1600	1674	1069	1218	1840	1791	1821	1650	11	30	49	38
May	1947	1743	1316	1198	2178	2085	2070	2070	13	31	58	51
June	2150	1801	1481	1217	2254	2166	2074	2173	13	30	67	56
July	2356	2070	1770	1525	2791	2794	2596	2680	13	31	77	62
Aug	1961	1973	1439	1497	2557	2431	2480	2356	13	31	75	60
Sept	1501	1913	1104	1551	2219	2106	2219	1886	11	30	64	51
Oct	973	1633	690	1381	1625	1501	1592	1147	9	31	54	43
Nov	568	1237	379	1075	1178	1052	1119	651	7	30	39	30
Dec	413	1024	263	898	958	833	891	495	7	31	31	22

Source: National Weather Service via Baker, 1976

that Missoula and western mountainous regions receive about 60-70% of Great Falls radiation, November through March, and about equal radiation in the summer half of the year.

Table 7.4

Observations of Percent Possible Sunshine

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Billings	.48	.54	.61	.59	.61	.64	.78	.77	.68	.61	.46	.45
Havre	.48	.60	.68	.65	.70	.73	.83	.82	.73	.63	.48	.45
Helena	.47	.54	.60	.57	.61	.62	.79	.75	.67	.60	.45	.43
Missoula	.28	.39	.48	.52	.57	.57	.80	.75	.65	.50	.32	.25
Great Falls	.49	.57	.67	.62	.64	.65	.81	.78	.68	.61	.46	.46

Source: National Weather Service

7.5 Models Used in Montana "Solar Analysis"

7.5.1 Definition of various receiving surfaces

7.5.1.1 The energy delivered by a solar system is dependent upon the orientation of the collector and on the season. The configuration which intercepts the most sunlight is that which is following the sun throughout the day so that the sun's rays are always striking the receiving surface perpendicularly. This is referred to as full sun tracking and requires motion about two axes (azimuth and elevation).

7.5.1.2 The next most promising orientation, and almost as effective as full tracking, is a rotation of the receiving plane about an axis which is parallel to the earth's axis. This requires motion about only one axis and it is referred to here as N-S axis polar.

7.5.1.3 Another promising orientation, and almost as good as full sun tracking, is called turntable tracking. (Swet, 1976) In this case, there is a turntable with a verticle axis upon which is mounted the receiving plane, raised 45° from level. The turntable rotates about one axis to follow the sun.

7.5.1.4 An orientation which is quite effective in the summer-half of the year is a rotation of the receiving plane about a north-south axis which is horizontal. This is a one-axis motion and is referred to here as N-S axis horizontal.

7.5.1.5 The last orientation is a static one. The receiving plane is inclined 45° from level and faces south. This is called 45° statistic. There is an important distinction here. The receiving plane is static, but somewhere in the system something may be tracking the sun; for example, a probe which is following the moving focus. Several interesting solar collection schemes fall into this class. These are collectors which seek to avoid the difficulties of moving a huge mirror by fixing the mirror rigidly and following the focus with a small probe. This apparent simplicity is paid for in reduced performance, for a static mirror can intercept only about two-thirds of the energy available to a moving one.

7.5.2 Method used to estimate solar radiation on various surfaces

Most solar measurements are taken by instruments mounted on a horizontal plane, and most solar equipment is mounted on some other (especially south-facing) plane. The expected solar radiation on any other plane than horizontal must be computed. This problem is classic, and methods for making these predictions have been devised and tested for south-facing surfaces. (Lui and Jordan, 1962)

The technique used by Lui and Jordan involves partitioning the total incoming radiation into two components: direct and diffuse. Direct radiation is the focusable portion with parallel rays. The amount of this type of radiation intercepted by an arbitrary receiving plane varies as the sine of the angle

between the rays and the receiving plane (or as the cosine of the angle between the sun rays and the plane normal).

Diffuse radiation comes from every direction and is caused by water vapor, various air molecules, and dust scattering of atmospheric light. Even on a very clear day, 15-20% of the radiation is diffuse. On a cloudy day, almost all the radiation is diffuse. The amount of diffuse radiation received on a plane varies with the amount of sky hemisphere available to a point in the plane. Even though diffuse radiation is more prevalent timewise, about 70% of the energy content of solar radiation is delivered as direct radiation.

Data for south-facing slopes for Northwest locations have been reduced and tabulated (Baker, 1975) using the techniques of Liu and Jordan. From this source have come the following estimates: horizontal direct and total radiation, and 45° south slope direct and total radiation, as shown in Tables 7.2 and 7.3.

Estimates for non-south-facing and various sun-following orientations are made by the direct beam hour method described below. Fundamental to this method and to others is the assumption that the direct sunlight occurs, on the average, uniformly throughout the day. Using the methods of Liu and Jordan, the average direct radiation received on a horizontal plane is estimated from measured total radiation on a horizontal plane. For an arbitrary receiving surface, the average daily direct radiation for each month is assumed to be the sum of hourly contributions from each daylight hour of a representative day.

The hour contribution will be proportional to the amount of sunlight intercepted by the receiving plane for that hour -- which depends on the angular relationship of the sun to the plane for that particular hour and month. This contribution can vary from 1, for the sun vector normal to the plane, to 0, if the sun vector is parallel to the plane. Explicitly defined, this is:

$$\text{hour contribution} = \text{unit receiving plane normal vector} \cdot \text{unit sun vector}$$

This is a vector dot product* equal to the cosine of the angle between the sun vector and the plane normal.

The daily sum of the hourly contribution is referred to as the direct beam hours (DBH):

$$DBH_{\substack{\text{month}\\\text{surface}}} = \text{daylight hours} \quad \text{surface unit normal} \cdot \text{unit sun for that hour and month}$$

The ratio of the direct radiation on one surface to the direct radiation on another differently oriented surface is the ratio of the DBH for those surfaces:

$$\frac{\text{Direct on surface}_1}{\text{Direct on surface}_2} = \frac{DBH_1}{DBH_2}$$

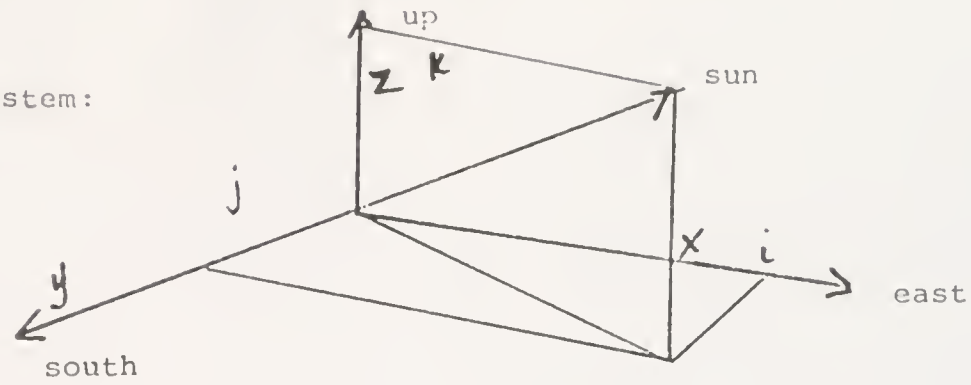
Therefore, if the direct radiation on a horizontal surface is known, then the direct radiation on surface S can be given as:

$$\text{Direct Radiation}_S = (\text{Direct Radiation}_{\text{horizontal}}) \frac{DBH_S}{DBH_{\text{horiz}}}$$

* The sun position is described as a three-component vector in all work here because it is more flexible.

The DBH for the various surfaces are given below.

coordinate system:



Horizontal DBH = $\sum_{\text{daylight hours}} k \cdot \text{sun vector}$
one for each month

Direct beam full sun track DBH = $\sum_{\text{daylight hours}} 1$

Turntable with 45° surface rotating to follow the sun DBH = $\sum_{\text{daylight hours}} \cos(\cos^{-1}(\text{sun}_z) - 45)$

Linear focus with axis parallel to earth axis (N-S parallel) DBH = $\sum_{\text{daylight hours}} \cos(\text{declination of sun})$

Note declination is only seasonally dependent. It is constant with respect to time of day.

Linear focus with E-W axis horizontal DBH = $\sum_{\text{daylight hours}} \sin(\cos^{-1}(\text{sun} \cdot i))$

Linear focus with N-S axis horizontal DBH = $\sum_{\text{daylight hours}} \sin(\cos^{-1}(\text{sun} \cdot j))$

Table 7.5

Direct Beam Hours for Latitude 48° North

	horizontal	beam	45° turntable	N-S parallel	N-S horizontal
Jan	2.03	7	6.16	6.15	3.71
Feb	3.08	9	8.10	8.73	6.00
Mar	4.63	11	10.13	10.89	8.83
Apr	6.39	11	10.71	10.89	9.87
May	7.85	13	12.44	12.35	12.35
Jun	8.51	13	12.44	11.96	12.53
Jul	8.24	13	12.45	12.09	12.48
Aug	7.32	13	12.36	12.61	11.98
Sep	5.47	11	10.44	11.00	9.35
Oct	3.60	9	8.32	8.82	6.36
Nov	2.25	7	6.25	6.65	3.87
Dec	1.92	7	6.09	6.51	3.62

This DBH method is flexible enough to handle situations where there is an obvious obstruction to some of the hourly contributions (such as a tree blocking the two o'clock winter sun, etc.). The method has also been adapted to computing structural shade factors on large solar-gain windows. (Reichmuth, 1976)

7.5.3 Method used to predict solar system performance under Montana conditions

The following is a prediction method which uses actual measured solar system test data in combination with local solar and weather data to predict the performance of a wide variety of different types ofsolar systems. The intent here is to identify the conspicuous performance distinctions associated with solar system orientation, operating temperature, concentration ratio, and optical efficiency.

Second order effects, mostly associated with linear concentrators, are: image spread, blocking of aperture by receiver tube, and light losses at the ends or at irregularities in the linear layout. Recent analysis (Duff and Shaner, 1976) shows that the second order effects are of the order of 15%. This correction is absorbed in the estimate of the system optical efficiency.

It is common practice to present the test results of a solar collection system in this fashion:

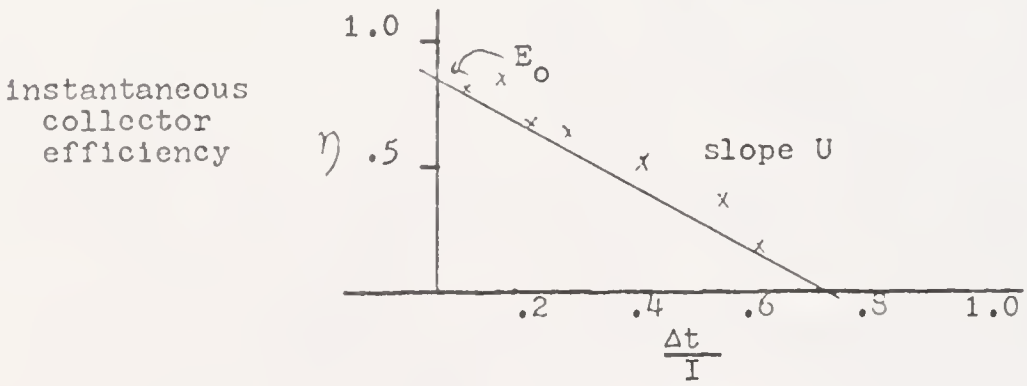


Figure 7.8
Collector Characteristics

where:

Δt is collector operating temperature - ambient

I is solar intensity

The measured performance usually fits a straight line quite well (The line does curve for the case of a low focus collector operating at high temperature).

The fact that the data behaves so well suggests that, to a first order, the collector performance can be represented by a very simple model, and that the complete collector performance can be represented by two parameters: E_o, the optical efficiency, and U, the heat loss coefficient. The efficiency, where E_o is the intercept of the test line with the efficiency axis and U is the slope of the line, is then:

$$\eta = E_o - U \frac{\Delta t}{I}$$

and heat collected per unit time = $IE_o - U\Delta t$.

Under certain conditions, unit time can be the full day and a daily average value can be used for $\underline{I}$ and Δt:

a) U, the heat loss coefficient, must be independent of $\underline{I}$. It is.

b) Also, the instantaneous heat loss rate, $U\Delta t$, must always be less than the heat input, IE_o.

If this condition is met, then Δt instantaneous can be replaced with Δt average and $\underline{I}$ instantaneous can be replaced with $\underline{I}$ average, without seriously altering the integrated estimates of the day heat gain. This condition is essentially met in a collection system well matched to its collection temperature.

The equation used to estimate the monthly energy collected by a system is:

$$Q = (I_m E_o + \Delta t_m U T_m) D_m$$

where:

Q = monthly heat gain, BTU

I_m = average daily radiation for that month of the appropriate type (direct only if collection involves focusing on the aperature of system; if system has a tracking aperature, then radiation data for that aperature orientation must be used.) BTU/ft^2 day

E_o = optical efficiency

Δt_m = average monthly collector temperature minus day ambient ^oF

U = heat loss coefficient, BTU/ft^2 $hr/^oF$

T_m = average day length for the month

D_m = number of days in month

The yearly energy collected is then just the sum of the monthly energy gains.

7.5.4 Model for estimating costs associated with solar energy collection systems

The capital costs of solar energy systems can usually be given in terms of dollars per square feet ($/ft^2) of collection area. A yearly energy yield per sq.ft. collection area under Montana conditions is computed in 1.4.3. From these, the capital cost associated with an installation capable of producing 10^6 BTU/yr is computed as follows:

$$\frac{\text{capital cost}}{\$/\text{mBTU/yr}} = \frac{\text{capital cost } \$/ft^2}{\text{yearly yield } \text{mBTU}/ft^2}$$

This is referred to as the capital cost per installed million BTU.

From this capital cost estimate, an estimate of the energy cost ($/mBTU) is made, based on the assumption of: 1), a yearly fixed charge rate of 10% of capital investment; and 2), operation and maintenance cost of $.50/mBTU (approximately equal to the 2mils/kwh industry standard. Energy cost:

$$\$/\text{mBTU} = \frac{\text{capital cost}}{\$/\text{mBTU/yr}} \times .10 + .50$$

It should be noted that this energy cost will be high in many cases (such as passive solar heating) where a fixed charge of .15 is unreasonably high and the operation and maintenance expenses are negligible.

*This includes a 6% per year inflation rate as well as the amortization of the capital, depreciation , profit, etc..

7.6 Specific Solar Systems: Description and Analysis

7.6.1 Double glazed south facing window with R10 nightdoor

A window exposed to the sun can be considered a flat plate solar collector operating at room temperature. In order to make this assumption, it is necessary that the heat entering through the window be useful either for immediate daytime heat needs or as heat storage in the thermal mass of the building. Also, it is necessary that the window be covered with an insulating door at night so that the daytime heat gain advantage of the window is not negated by a corresponding large nighttime heat loss. This essentially describes a passive solar heat collection system. Such a system is essentially common building practice and the costs to be associated with it are as follows:

$5.00/sq.ft. double glazing,
$3.00/sq.ft. insulating door
$8.00/sq.ft. total

It should be noted that the gain from this system which occurs in the summer (June, July, August) is not useful. Therefore, the useful net gain of this system is 202,239 Btu/sq.ft., and this gain is the basis of the heat cost projections associated with this system.

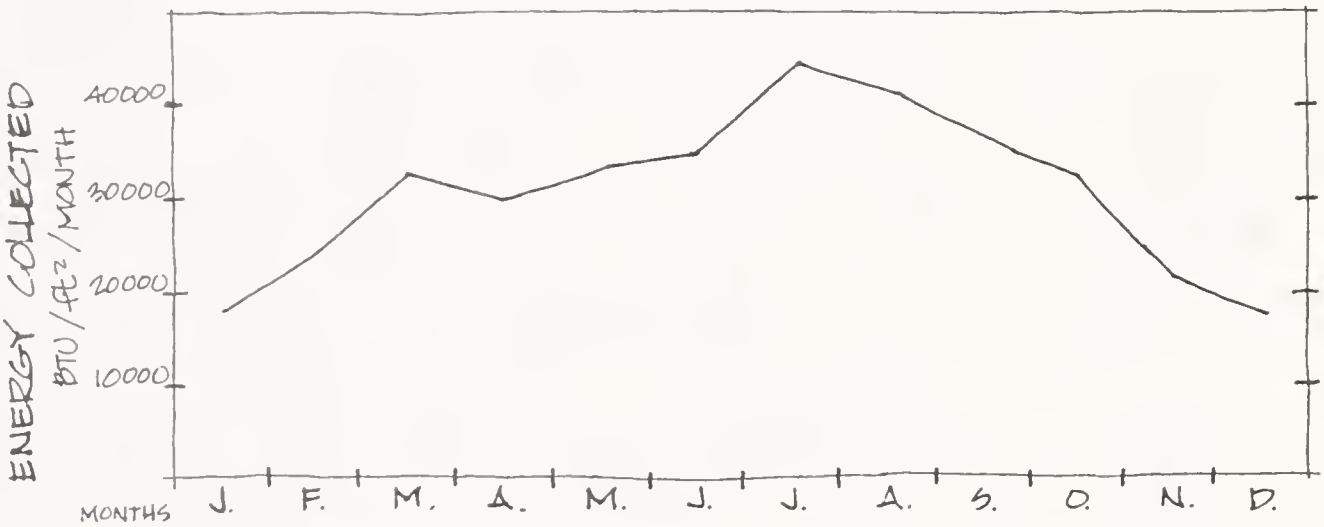
ANALYSIS SUMMARY

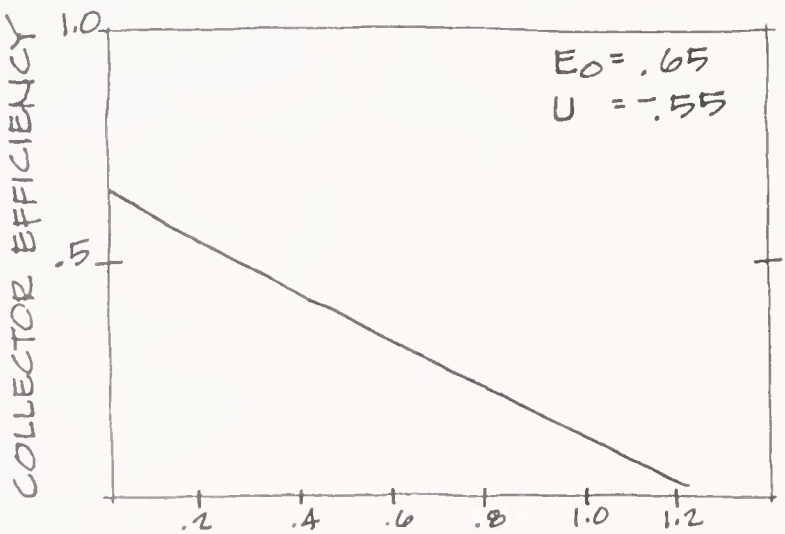
• DOUBLE GLAZED WINDOW, W/ R=10 DOOR

OPERATING TEMP. = 70°
45° SOUTH FACING SURFACE
TOTAL RADIATION AT GREAT FALLS
NET USEFUL YIELD = 202239 BTU/ft²

COSTS: $8.00/ft² ($500-glass, $300-door)
$39.60/MBTU/YR.
$ 4.46/MBTU

MONTHLY COLLECTION SYSTEM PERFORMANCE





Δt/I, COLLECTOR CHARACTERISTICS

7.6.2 High quality flat plate collector

The flat plate collector is the most widely manufactured and tested solar collection device. These have been widely tested by NASA at the Lewis Research Center (Johnson, 1976), and it is from this source that the collector characteristics are taken. One of the best performing collectors was chosen for this analysis, so the collector performance represented here corresponds to the best of the state of the art.

Compared to other solar collection systems, flat collectors perform relatively poorly in Montana. This is because flat plate collector performance is quite sensitive to low ambient temperatures. Flat plate collectors can be expected to perform much better in warmer, hazier regions.

Figure 7.10

ANALYSIS SUMMARY

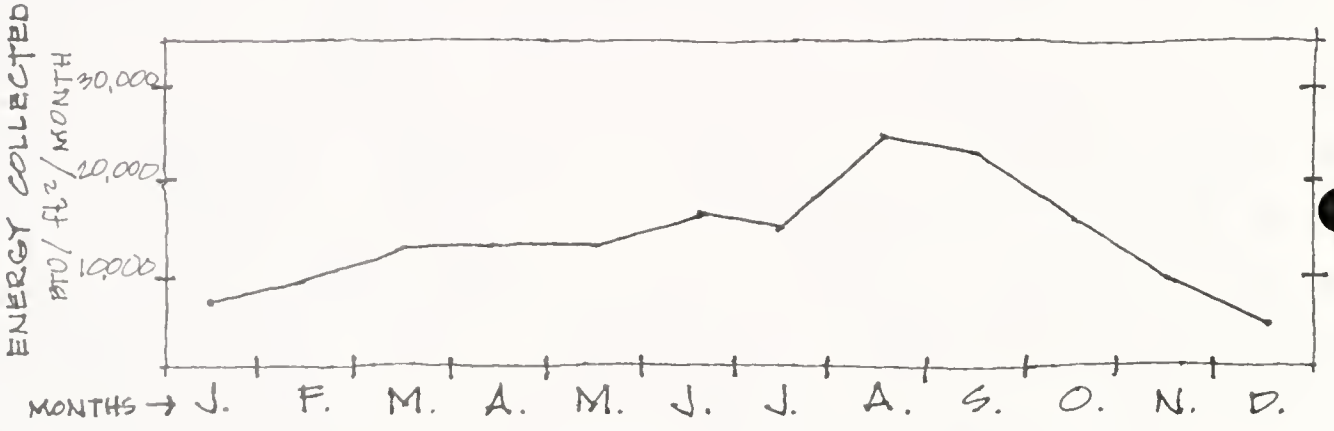
HIGH QUALITY FLAT PLATE COLLECTOR
(DOUBLE GLAZED W/ SELECTIVE SURFACE)

OPERATING TEMP. = 130° F.
45° SOUTH FACING SURFACE
TOTAL RADIATION AT GREAT FALLS
YEARLY YIELD = 172140 BTU/ft.²

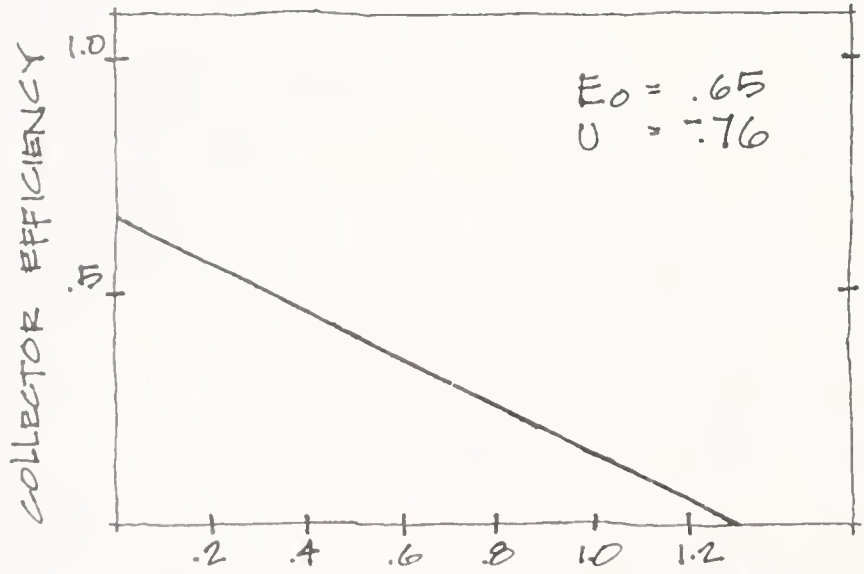
COSTS:

INSTALLED SYSTEM
$23.00/ft.²
$133/MBTU/YR.
$13.80/MBTU (SHIPPEE, 1976)

HOME MADE SYSTEM
$6.00/ft²
$34.80/MBTU/YR.
$3.98/MBTU



MONTHLY COLLECTION SYSTEM PERFORMANCE



At/I, COLLECTOR CHARACTERISTICS
(JOHNSON, 1976)

7.6.3 Refractive concentrator, Northrup design

This is an off-the-shelf solar collection system currently installed at several locations throughout the country. It has proved to be quite efficient and this efficiency can be traced to three important qualities:

1) It tracks the sun, therefore receiving more sun.
2) The lens is of efficient enough design that the optical efficiency is higher than that of a flat plate collector with two covers.
3) The heat loss rate is low because of concentration, an important quality in cold climates.

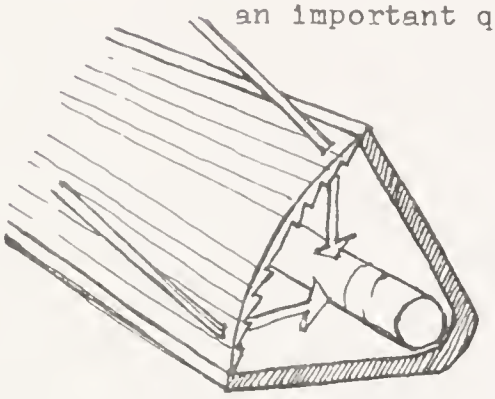


Figure 7.11

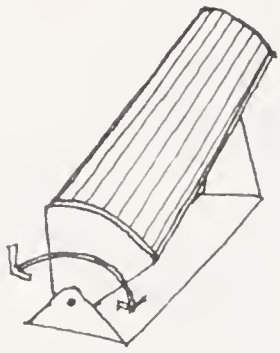


Figure 7.12

These collectors must track the sun and, in this case, the collector is mounted with its rotation axis parallel to the earth's axis.

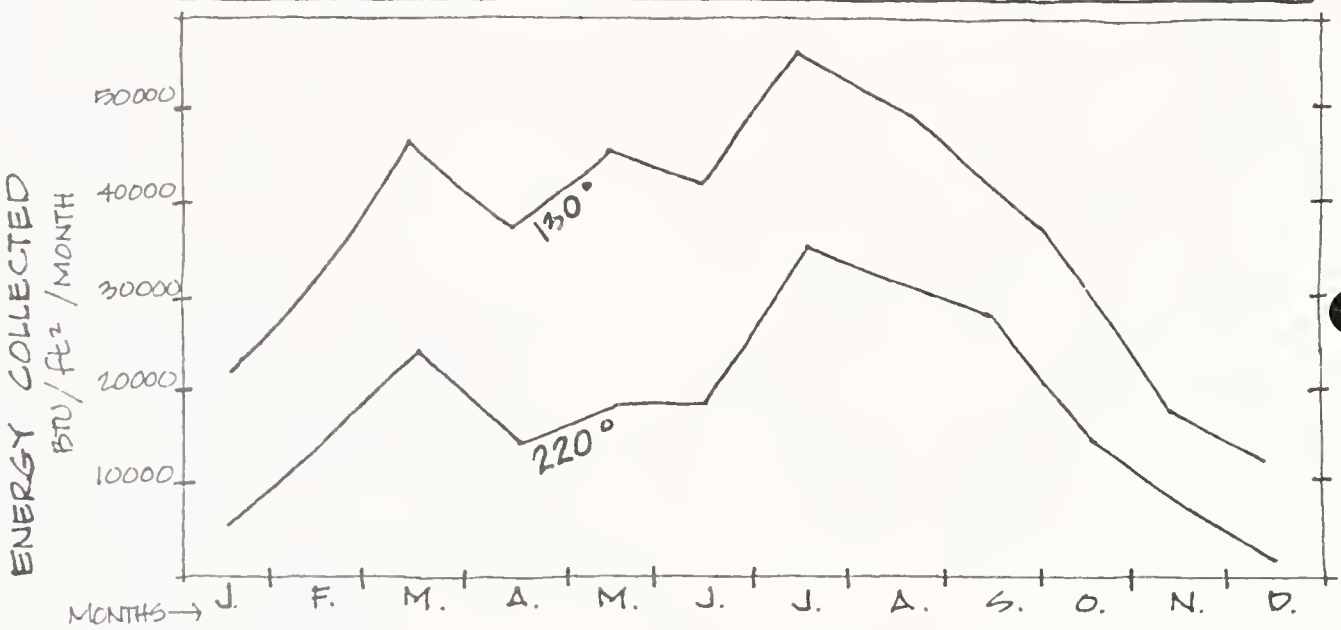
This collection system has been evaluated at two generating temperatures: 130°F for hot water use, and 220°F for use with very hot water and air conditioning.

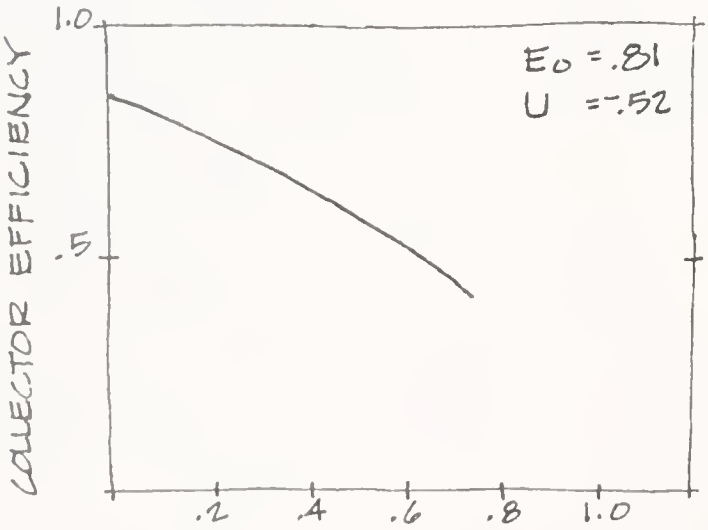
ANALYSIS SUMMARY

NORTHRUP REFRACTIVE CONCENTRATOR

OPERATING TEMP. = 220°F., 130°F.
TRACKING ABOUT POLAR AXIS
DIRECT RADIATION AT GREAT FALLS
YEARLY YIELD = 424448 BTU/ft² (@130°F)
216720 BTU/ft² (@ 220°F)
COSTS:
$21.50/ft² (NORTHRUP, 1976)
$50.70/MBTU/YR (@130°F) $99.08 MBTU/YR (@220°F)
$5.57/MBTU (@130°F) $10.41 /MBTU (@220°F)

MONTHLY COLLECTION SYSTEM PERFORMANCE





Δt/I COLLECTOR CHARACTERISTICS

7.6.4 Evacuated tube collector, Owens Illinois design

The evacuated tube collector is an attempt to produce an efficient solar collector by markedly reducing the heat loss rate through the use of a vacuum which isolates an inner receiver tube from an outer glass cover. The device is made from tubular glass which is a very effective way to use glass.

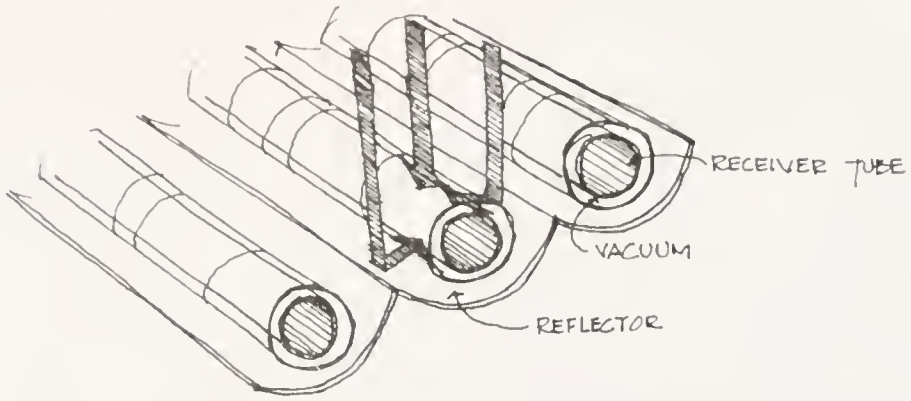


Figure 7.14

This collector does not rely on focusing, therefore it has no need to track the sun and it can use the diffuse component of the solar radiation. This collector has been evaluated at 220°F for very hot water and air conditioning applications, and at 130°F for hot water applications. The heat loss rate for this collector is so low that there is no marked benefit to operating it at a lower temperature (130°F versus 220°F).

ANALYSIS SUMMARY

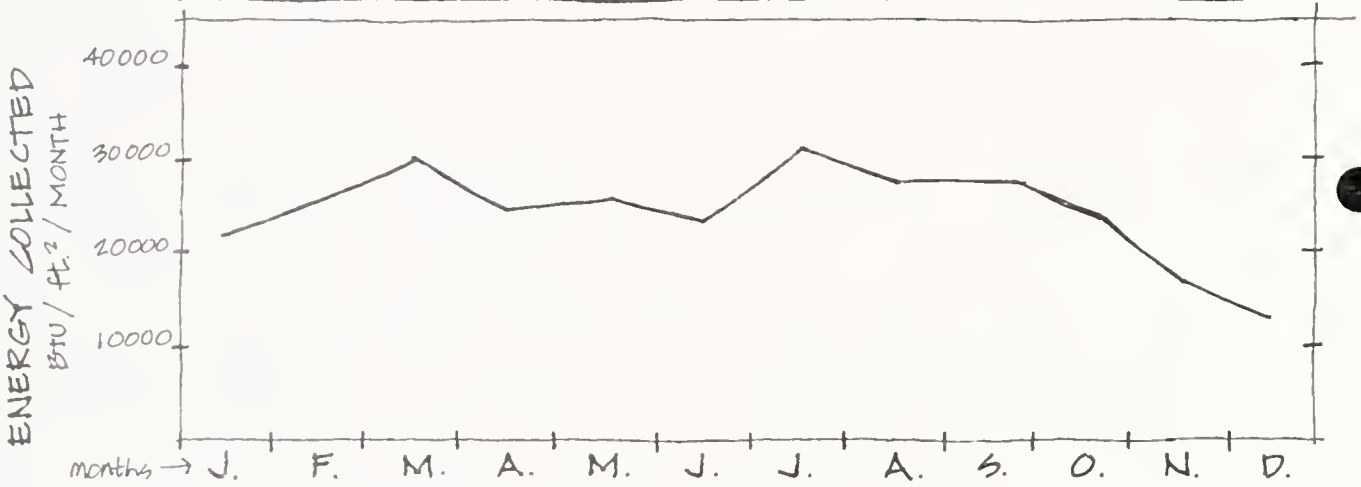
EVACUATED TUBE COLLECTOR

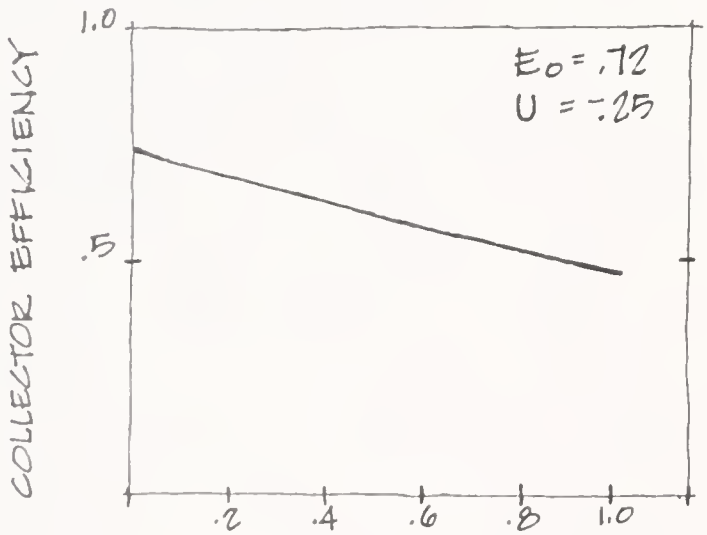
(OWENS ILLINOIS DESIGN)

OPERATING TEMP. = 220° F.
45° SOUTH FACING
TOTAL RADIATION AT GLASGOW
YEARLY YIELD = 299334 BTU/ft.²

COSTS: $28.00 /ft²
$93.65/MBTU/yr.
$ 9.86 /MBTU

MONTHLY COLLECTION SYSTEM PERFORMANCE





Δt/I COLLECTOR CHARACTERISTICS

7.6.5 3X concentrator with vacuum receiver and selective surface

This type of collector is currently under development at Argonne National Labs. It has not yet been tested as a complete system. It is included here because it is a sophisticated use of the evacuated tube concept and it represents a simple and inexpensive technique for generating steam. The system is intended to be non-tracking by utilizing an ingenious "light funnel" type concentrator (compound parabolic concentrator) which has been under development at Argonne Labs for several years. In this analysis the system will also be evaluated for turntable tracking (see Section 7.4) because this gives a substantial increase in yield for marginal additional expense.

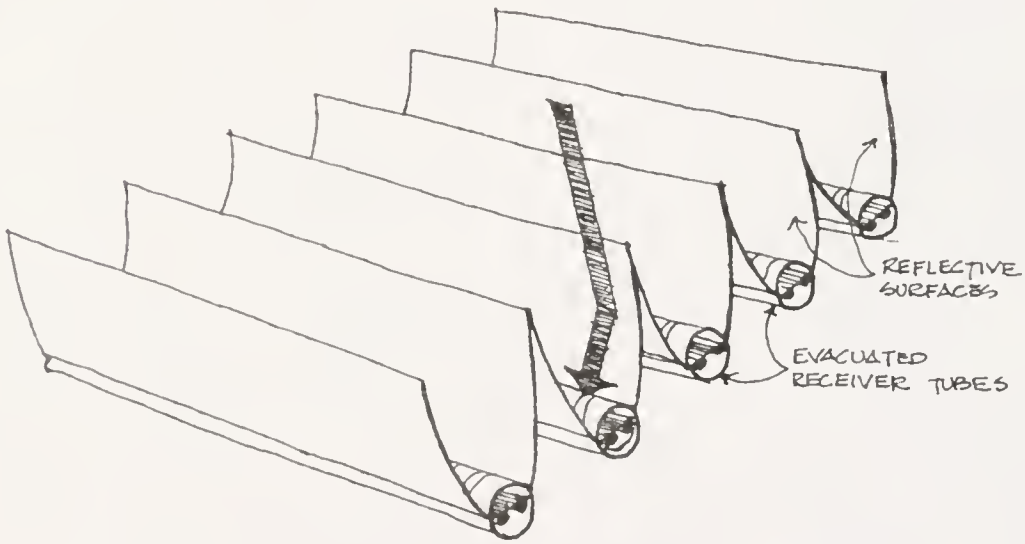


Figure 7.16

The cost associated with this system by the developers is $10 per sq.ft. (Allen et al, 1976), which is reasonable since the expensive portion, the evacuated receiver, is replaced for two-thirds the area by an inexpensive reflector. For the tracking case, $3 per sq.ft. is added to account for the additional expense of the tracking mechanism.

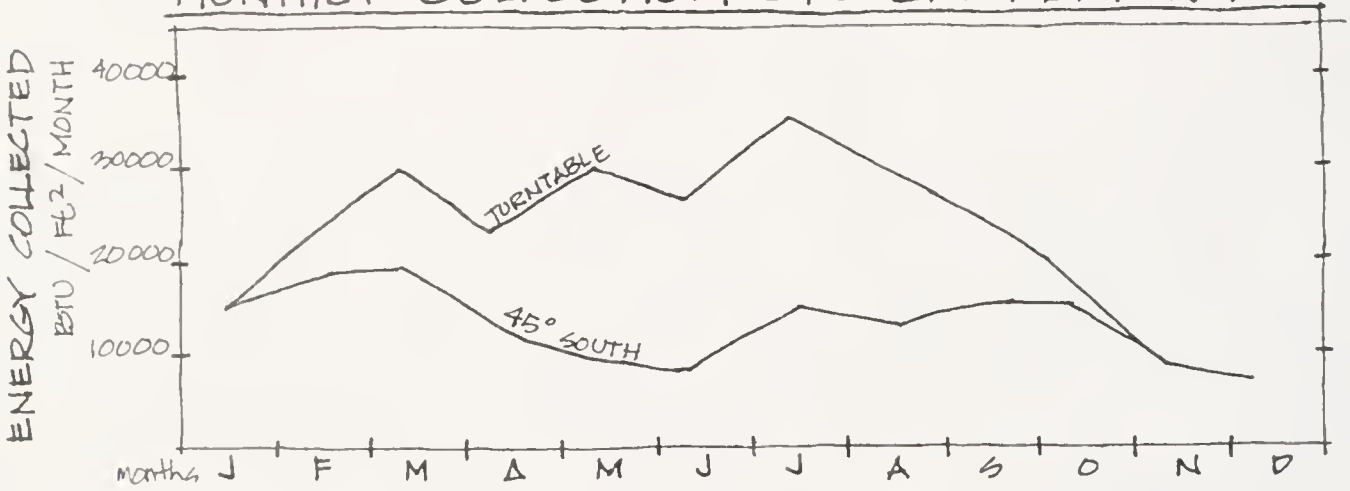
ANALYSIS SUMMARY

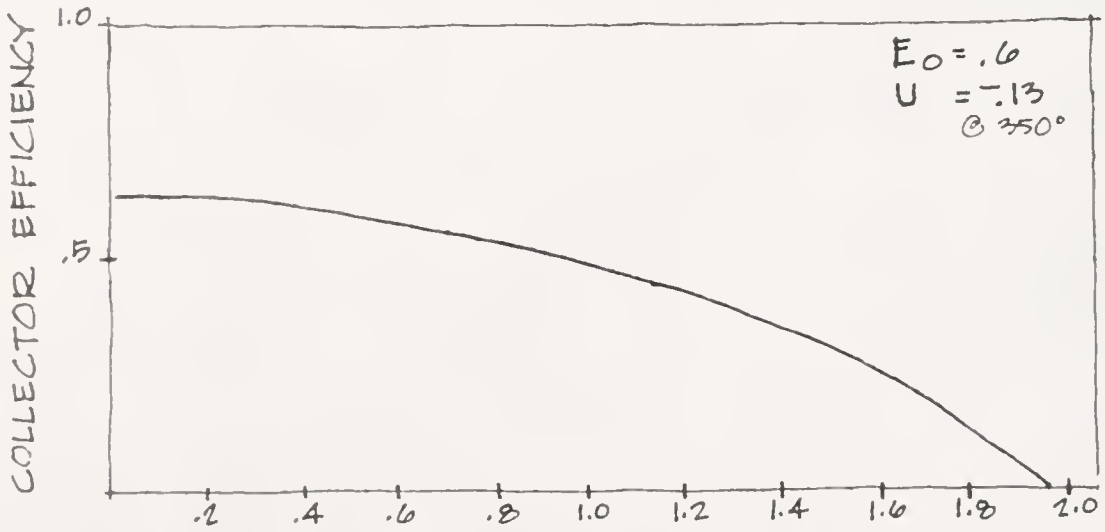
3× CONCENTRATOR w/ VACCUM RECEIVER

OPERATING TEMP. = 300° F
45° SOUTH FACING, TURNTABLE
DIRECT RADIATION AT GLASGOW
YEARLY YIELD = 190488 BTU/ft² (STATIONARY)
302533 BTU/ft² (TURNTABLE)

COST:	STATIONARY	TURNTABLE
	$10.00/ft²	$13.00/ft²
	$52.60/MBTU/YR.	$43.05/MBTU/YR.
	$ 5.76 /MBTU	$ 4.81 /MBTU

MONTHLY COLLECTION SYSTEM PERFORMANCE

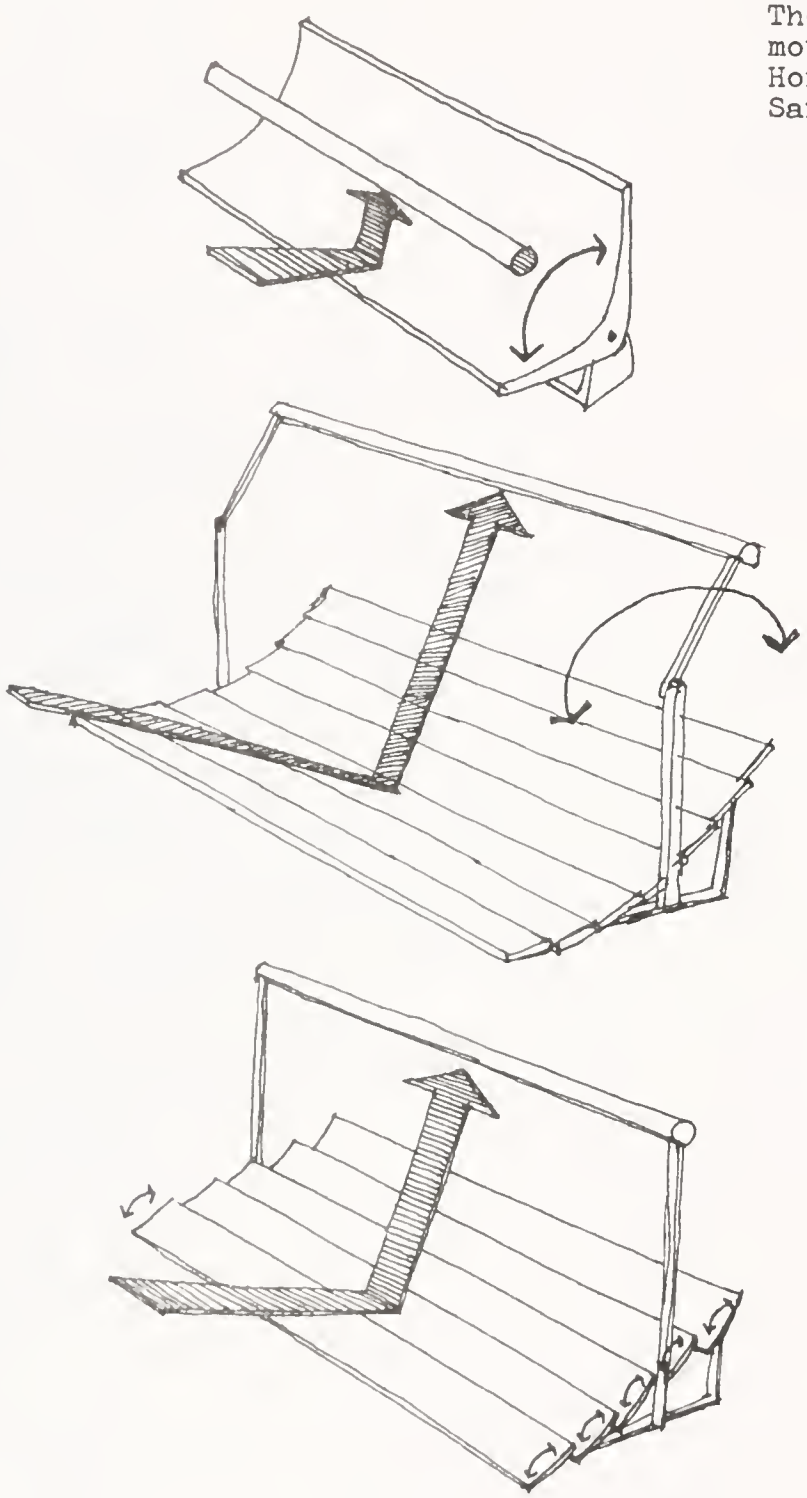




Δt/I COLLECTOR CHARACTERISTICS

7.6.6 Large scale linear concentrators

Linear concentrators of the general types illustrated below have been built and tested as small prototypes.

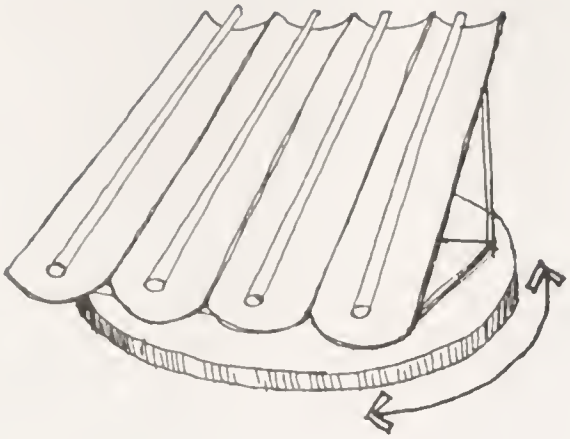


The whole parabolic trough moves to follow the sun.
Honeywell Corp.,
Sandia Labs, Albuquerque NM

Mirror slats fixed, absorber tube moves.
General Atomic Corp.,
Georgia Tech.

Absorber tube is fixed, slats move to keep focus on tube.
ITEK Corp.,
Sheldahl Corp.

Figure 7.18



Mirrors and absorber tubes rigid relative to one another, and whole array rotates to keep focus. (Swet, 1976)

Figure 7.18

Large scale prototypes of the first three of these systems are being built in the context of the Sandia Labs Albuquerque Solar Total Energy Program, due to be completed by 1978.

Cost estimates have been made for the first three systems (Duff and Shaner, 1976) based on large-scale manufacturing of the systems. In all three cases, the costs were slightly less than $10 per sq.ft. for the collection system. The additional costs associated with interfacing the collection system with the heat-using portion of a total system will be considered to be equal to the costs of the collection system: $10.00/ft^2. This is probably conservative, but it is based on experience in the total solar energy program, where the costs of the electrical generation subsystem are expected to be about the same as the solar collection subsystem (Leonard, 1976, Personal).

The collector characteristics have been derived from the operating experience with the Honeywell system (Zoerb, 1976). A representative collector is evaluated in three orientations.

ANALYSIS SUMMARY

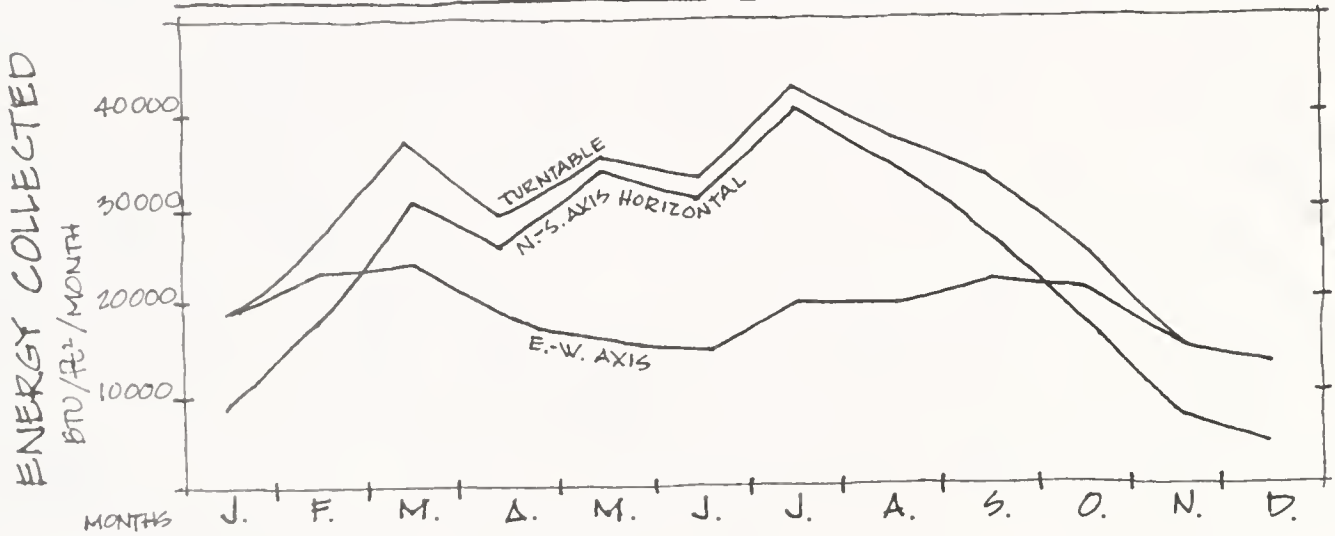
LINEAR CONCENTRATORS

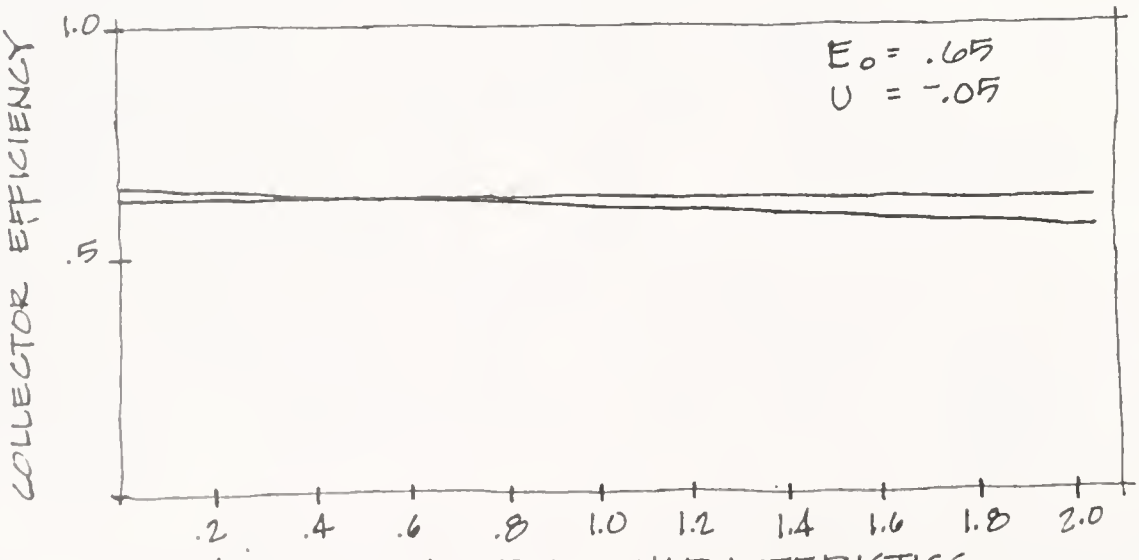
OPERATING TEMP. = 600° F.
E-W. AXIS, N-S. AXIS, TURNTABLE
DIRECT RADIATION AT GLASGOW
YEARLY YIELD = 2355693 BTU/ft² (E.-W.), 289079 BTU/ft² (N.-S.)
3560239 BTU/ft² (TURNTABLE)

COSTS:

E-W.	N-S.	TURNTABLE
$10.00/ft²	$10.00/ft²	$10.00/ft²
$42.60/MBTU/YR.	$34.60/MBTU/YR.	$28.09/MBTU/YR.
$ 4.76/MBTU	$ 3.96/MBTU	$ 3.31/MBTU

MONTHLY COLLECTION SYSTEM PERFORMANCE





Δt/I, COLLECTOR CHARACTERISTICS

7.6.7 Heliostat/central receiver system

These systems have been designed for the large scale generation of electricity, but they could be used as well as high temperature sources.

The individual components of a large scale system have been fabricated and tested, but the first full scale prototype ($10MW_e$) is not due to be completed until 1980, and a 50-100 MW plant is scheduled for completion in 1985.

The Martin Marietta Aerospace Corporation has done preliminary design work on the 10 MW pilot plant and has built and tested several system components. System cost and performance data are taken from the Martin Marietta work. (Blake, 1976)

Figure 7.20

ANALYSIS SUMMARY

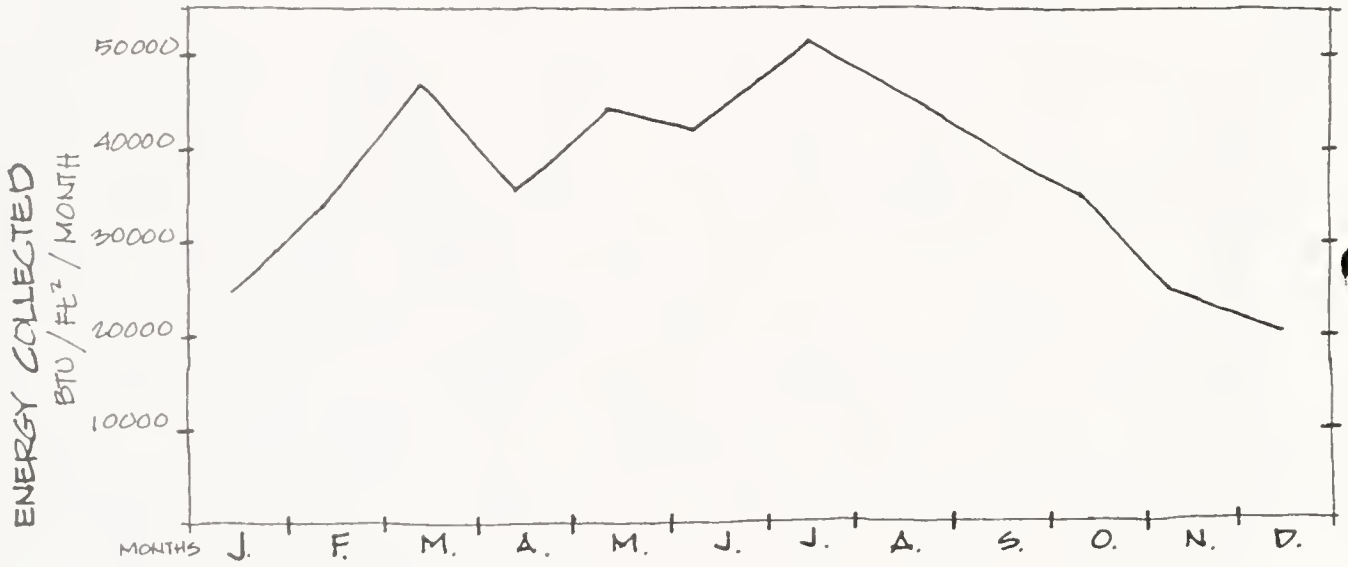
HELIOSTAT CENTRAL RECEIVER

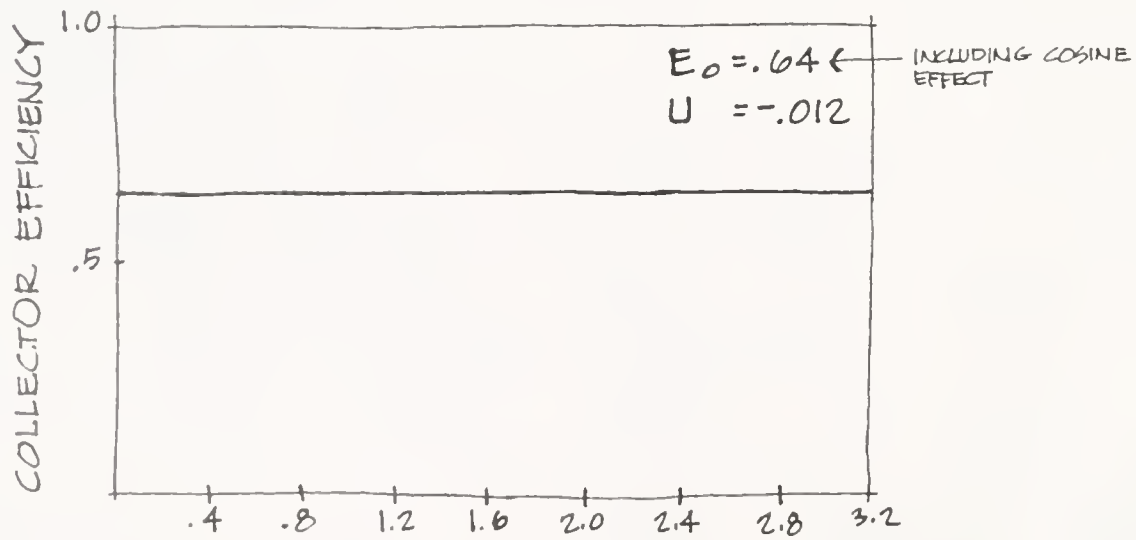
OPERATING TEMP. = 1000° F
FULL SUN TRACKING
DIRECT RADIATION AT GLASGOW
YEARLY YIELD 441063 BTU/ft²

COST:

THERMAL ONLY	ELECTRIC
$26.26 /ft²	$28.71 /ft²
$59.54 /MBTU/Yr.	$200.64 /MBTU electric/yr.
$ 6.45/MBTU	70 MILS/KWH

MONTHLY COLLECTION SYSTEM PERFORMANCE





Δt/I COLLECTOR CHARACHTERISTICS

7.6.8 Photovoltaic Cells

Photovoltaic systems are the simplest and possibly the most promising of systems for generating solar electricity. The costs in this field change dramatically from year to year. Three approaches are being pursued which show promise of substantial reductions in cost per kw:

1) concentration of light on photovoltaic cells
2) continuous ribbon or sheet growth of cells, eliminating the current practice of slicing silicon wafers
3) scaling manufacturing to terrestrial quantities and standards

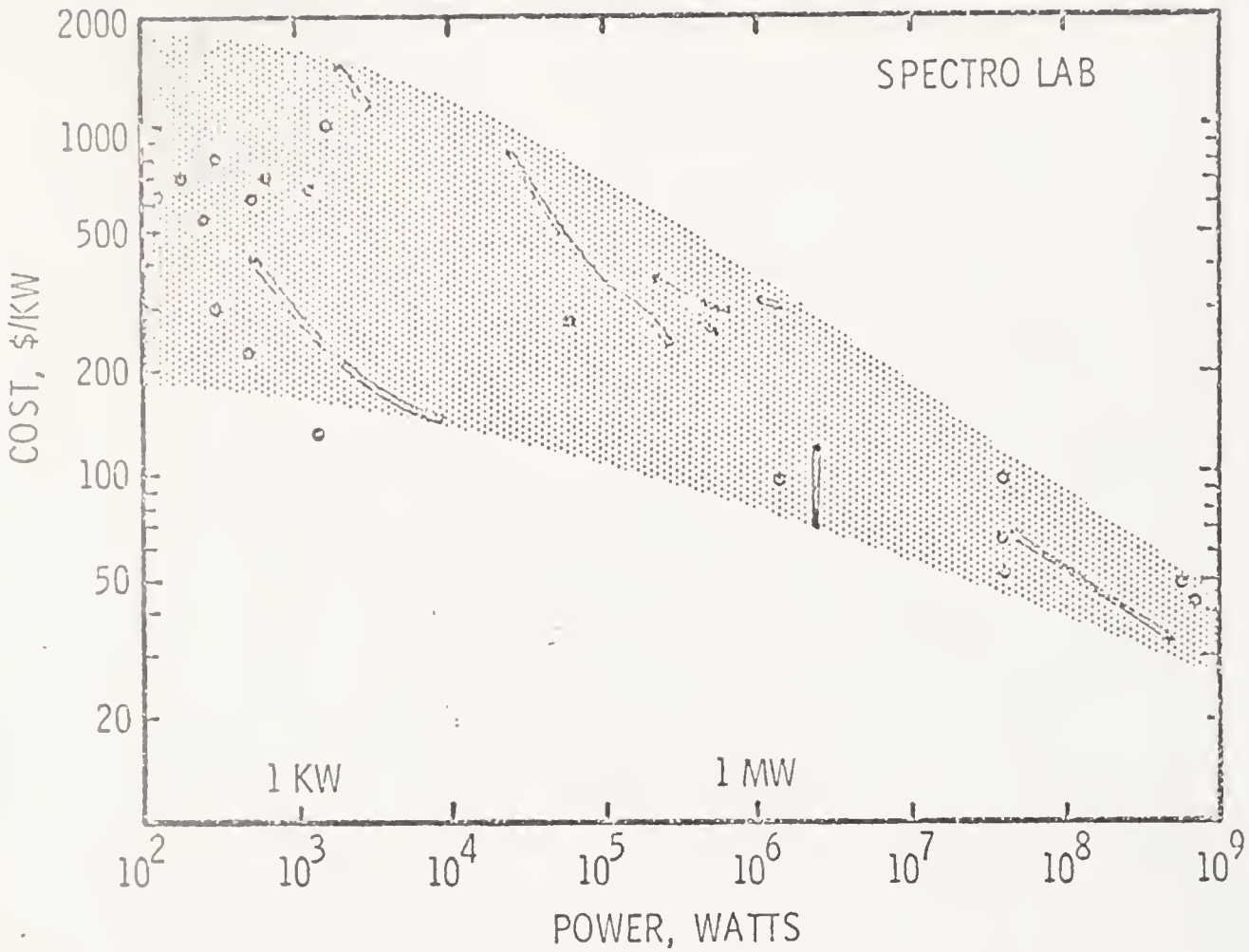
Target costs for these approaches are given in the following table (from Sandia Albuquerque and Jet Propulsion Laboratory, Pasadena, California, JPL):

Table 7.6

Target costs $/kw

Sandia (concentration)	JPL (manufacturing & continuous growth)
	IN PLAT ARRAYS
1976	20,000
1977	
1978 2,000	7,000
1980 1,000	5,000
1982 500	3,000
1983	1,000
1985 250	
1986	500

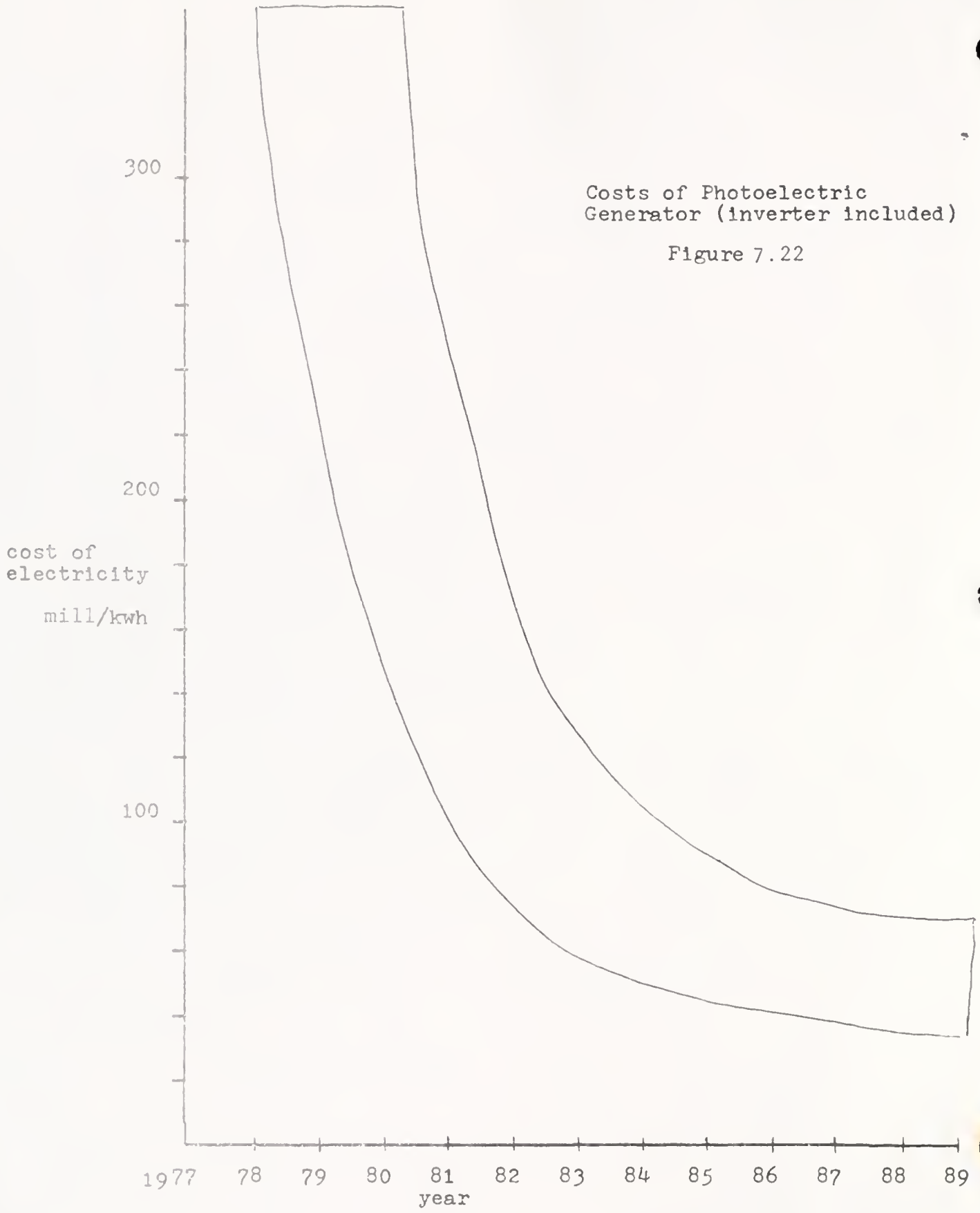
These target costs are per peak kw of the collector subsystem only. In practice, the current output from this system will need to pass through an inverter for conversion to AC. A chart of inverter cost versus power (Schueler, 1976) is given in Figure 7.21 From this I will assume an inverter cost of $150/kw for plants of 1 MW or larger. I will assume a plant factor of .15 for photovoltaic applications, even though higher plant factors could be achieved through one sort some sort of tracking. Based on these assumptions, a range of cost projections for photovoltaic electric generation is presented in Figure 7.22.



INVERTER COST VERSUS POWER

Figure 7.21

Source: Schueler, 1976



Costs of Photoelectric
Generator (inverter included)

Figure 7.22

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PERSONAL COMMUNICATIONS WITH ECOTOPE GROUP, 1976-1977:

Bolton, Charles, of Martin Marietta Solar Thermal Electric Program, concerning adjustments and considerations ofor siting heliostat systems in northern sites, optical efficiency (cosines) of heliostat systems. Sensitivity of system to less than full sunlight, operation of turbine at less than full power.

Brualdi, Tom, concerning cost estimates of heliostat systems, economics of various thermal storage options, receiver boiler characteristics.

Goralnick, Norman S., Manager of ITEK solar energy program concerning operating efficiency of ITEK solar concentration and costs of system details of integrating collector field with turbine generator and implementation plans.

Kaplan, George, of ERDA, head of solar thermal electric energy division, concerning projected costs of electric energy generated by the heliostat central receiver approach.

Leonard, James, Manager of Sandia, Albuquerque, total energy program concerning integration of linear collector systems with electric generating facilities, costs and timetables for completion of test systems.

Russell, John L., manager of General Atomis solar energy program concerning efficiencies and operating modes of the fixed mirror moving receiver solar concentrator and implementation plans.

Zoerb, Edward, manager of Honeywell solar energy program, concerning operating efficiency of Honeywell system, costs.